Design of Structures to Resist the Pressures and Movements of Expansive Soils

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Acknowledgements

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Topics (1/2)

- Soil properties
- Suction envelopes
  - Climates
  - Trees
  - Drainage
- Pavement design
  - Concrete and asphalt
  - Stabilized layers
  - Vertical and horizontal moisture barrier
Topics (2/2)

- Shrinkage cracking design
- Shallow slope failure
- Slab-on-ground design
- Drilled pier design
  - Lateral pressures
  - Stresses, strains, movements
  - Comparison with field measurement
- Retaining wall design
  - Lateral pressures
  - Stresses, strains, movements
  - Comparisons with measurements
Volume Change

\[ \frac{\Delta V}{V} = -\gamma_h \log_{10} \left( \frac{h_f}{h_i} \right) - \gamma_\sigma \log_{10} \left( \frac{\sigma_f}{\sigma_i} \right) \]  
(Lytton, 1977)

\[ \frac{\Delta H}{H} = f \left( \frac{\Delta V}{V} \right) \]

\[ f = 0.67 - 0.33\Delta pF \]

\[ f = 0.5 \text{ when drying; } \]
\[ f = 0.8 \text{ when wetting } \]

\[ \Delta = \sum_{i=1}^{n} f_i \left[ \frac{\Delta V}{V} \right] \Delta z_i \]

Volume–Mean Principle Stress-Suction surface
Volume Change

6500 Data from SSL
Of National Soil Survey Center

Partitioning Database
on Mineral Classification

(Covar and Lytton, 2001)
Volume Change

\[
\sigma_{h1} = h_1 + \theta \theta
\]

\[
\begin{bmatrix}
\%
\end{bmatrix}
\]

\[
\gamma_\sigma = \gamma_h \left[ 1 + \frac{h}{\theta \left( \frac{\partial h}{\partial \theta} \right)} \right]
\]

\[
\gamma_h = \gamma_0 \left[ \frac{\% - 2 \mu m}{\% - \text{No. 200 sieve}} \right]
\]

\[
\% f_c = \frac{\% - 2 \mu m}{\% - \text{No. 200 sieve}}
\]

Zone III (Covar and Lytton, 2001) (Lytton, 1994)
Exponential Suction Profile for Extreme Wetting and Drying Condition

\[ U(Z,t) = U_e + U_o \exp \left( -\frac{n\pi Z}{\alpha} \right) \cos \left( 2\pi n t - \sqrt{\frac{n\pi}{\alpha}} Z \right) \]

Mitchell (1979)

\[ U(Z) = U_e + U_o \exp \left( -\frac{n\pi Z}{\alpha} \right) \]

Fort Worth Interstate 820

Moisture Active zone
Volume Change

\[
\frac{\Delta V}{V} = -\gamma_h \log_{10} \left( \frac{h_f}{h_i} \right) - \gamma_\sigma \log_{10} \left( \frac{\sigma_f}{\sigma_i} \right)
\]  
(Lytton, 1977)

\[
\frac{\Delta H}{H} = f \left( \frac{\Delta V}{V} \right)
\]

\[
f = 0.67 - 0.33\Delta pF
\]

\[
\left( f = 0.5 \text{ when drying}; \quad f = 0.8 \text{ when wetting} \right)
\]

\[
\Delta = \sum_{i=1}^{n} f_i \left[ \frac{\Delta V}{V} \right] \Delta z_i
\]

Volume–Mean Principle Stress–Suction surface
Lateral Pressure Coefficients

<table>
<thead>
<tr>
<th>Conditions</th>
<th>$K_o$ (after McKeen, 1981)</th>
<th>e</th>
<th>d</th>
<th>k</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Drying (Active)</td>
<td>1/3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Equilibrium (at rest)</td>
<td>1/2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Wetting (within movement active zone)</td>
<td>2/3</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Wetting (below movement active zone)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Swelling near surface (passive earth pressure)</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

$L_0 = e \left( \frac{1 - \sin \phi'}{1 + \sin \phi'} \right) \left( \frac{1 + d \sin \phi'}{1 - k \sin \phi'} \right)^n$

(Lytton et al., 2006)

$\phi' = 0.0016PI^2 - 0.3021PI + 36.208$

$R^2 = 0.9978$

(after Holtz and Kovacs, 1981)
Volumetric Moisture Content and Suction Curves

\[ pF_0 = 5.622 + 0.0041(\% \text{ clay fines}) \]

\[ S = -20.29 + 0.1555(\text{LL}) - 0.117(\text{PI}) + 0.0684(\#200) \]

(Lytton et al., 2006)
Pavement Design on Expansive Soils
Pavement Treatments

Pavement Section

Subgrade

Inert soil

Stabilized Soil

Pavement

Barrier

Width of Pavement, 83 FT

6 FT 12 FT 12 FT 12 FT 7 FT 10 FT

27 FT
Transverse Distribution of Vertical Movements

Swelling

Shrinkage

Section A
Section B
Section C

(in)
3.5
2.5
1.5
0.5
-0.5
-1.5

0
10
20
30
40

d (ft)
Field Conditions

\[ U_e = 3.5633 \exp(-0.0051TMI) \]

Field capacity, Equilibrium, pF, Wilting point 4.5 pF, Root zone, Moisture active zone

\[ U(Z) = U_e \pm U_0 \exp \left( -\frac{n\pi Z}{\alpha} \right) \]
Climatic Conditions
Thornthwaite Moisture Index (TMI, 1948)

Roadside Drainage Conditions

\[
TMI = \frac{100R - 60DEF}{E_p}
\]

\(R\) = runoff moisture depth
\(DEF\) = deficit moisture depth
\(E_p\) = evapotranspiration
Calculated Vertical Movement

![Graph showing calculated vertical movement](image-url)
Comparison of PVR with Case Study

Results

No Treatments

Swell

Shrink

IN

Fort Worth A

B

C

Edge

Outer Wheel Path

Edge

Outer

New method

PVR

Atlanta

Austin

M

F

18
Acceptable Predicted Performance

Flexible Pavement
Fort Worth Interstate 820 A
Acceptable Predicted Performance

![Graph showing predicted performance over time for various pavement types.

- **Rigid Pavement**
- **Austin State Route 1**

Legend:
- LTS 1.5 ft, Inert 1.8 ft
- LTS 2.0 ft, Inert 1.5 ft
- LTS 2.0 ft, Inert 2.0 ft
- LTS 2.0 ft, Inert 3.0 ft

Graphs illustrate the predicted performance over time for different pavement conditions.
Predicted Roughness with Time

Loss of Serviceability

Increase of Roughness

Fort Worth Interstate 820 B

Soil
Traffic
Total

SI

IRI

Time (yrs)
SUBGRADE MOVEMENTS COMPARED WITH PVR FOR A MINIMUM ACCEPTABLE TREATMENT

<table>
<thead>
<tr>
<th>Flexible Pavement</th>
<th>New Method</th>
<th>PVR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Edge</td>
<td>Outer</td>
</tr>
<tr>
<td>Case Sites</td>
<td>Swell</td>
<td>Shrink</td>
</tr>
<tr>
<td>Fort Worth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.02</td>
<td>1.12</td>
</tr>
<tr>
<td>B</td>
<td>0.78</td>
<td>0.72</td>
</tr>
<tr>
<td>C</td>
<td>0.72</td>
<td>0.73</td>
</tr>
<tr>
<td>Atlanta</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>1.06</td>
</tr>
<tr>
<td>Austin</td>
<td>Main</td>
<td></td>
</tr>
<tr>
<td>Frontage</td>
<td>0.37</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Avg. 0.67 in 1.1 in
Longitudinal Cracking over Expansive Soil

- Expansive soil
  - Experience volumetric change when subjected to moisture variation
- Longitudinal crack
  - Initiate in shrinking expansive subgrade
  - Propagate to pavement surface
Practice of Geogrid Reinforcement

FM1915 (Milam County, Texas)
Practice of Lime Treatment
Stress Analysis on Subgrade Soil

• Stress variable for saturated soil: $\sigma - u_w$
• Stress variable for unsaturated soil: $\sigma - u_a, u_a - u_w$
• Soil suction
  - The affinity of soil for water
  - Matric suction: negative water pressure
  - Osmotic suction: soluble salts in the soil water
• Constitutive equation to estimate the volumetric strain of unsaturated soil:

$$\frac{\Delta V}{V} = -\gamma_h \log_{10} \left( \frac{h_f}{h_i} \right) - \gamma_\sigma \log_{10} \left( \frac{\sigma_f}{\sigma_i} \right) - \gamma_\pi \log_{10} \left( \frac{\pi_f}{\pi_i} \right)$$
\[
\frac{\Delta V}{V} = -\gamma_h \log_{10}\left(\frac{h_f}{h_i}\right) - \gamma_\sigma \log_{10}\left(\frac{\sigma_f}{\sigma_i}\right) - \gamma_\pi \log_{10}\left(\frac{\pi_f}{\pi_i}\right)
\]

where

\[
\frac{\Delta V}{V} = \text{volumetric strain;}
\]

\(h_i\) = initial value of matric suction;

\(h_f\) = final values of matric suction;

\(\sigma_i\) = initial value of mean principle stress;

\(\sigma_f\) = finial value of mean principle stress;

\(\pi_i\) = initial value of osmotic suction;

\(\pi_f\) = finial value of osmotic suction;

\(\gamma_h\) = matric suction compression index;

\(\gamma_\sigma\) = mean principal stress compression index; and

\(\gamma_\pi\) = osmotic suction compression index.
Without Geogrid Reinforcement…

Asphalt
Crack
Base
Subgrade (Expansive soil)
With Geogrid Reinforcement...

Subgrade (Expansive soil)

Asphalt

Geogrid

Base

$C_L$
Mechanism of Geogrid Reinforcement
Transverse Stress Distribution in Pavement (Full Restraint)
Transverse Stress Distribution in Pavement (Crack at Edge of Shoulder)
Transverse Stress Distribution in Pavement with Treated Layer
Slab-on-Ground Design
EXAGGERATED EXAMPLE OF DAMAGE TO A HOME AS A RESULT OF SHRINKING OR SWELLING SOILS
Example 1: Center Lift ($em=5.5\text{ ft}$, $ym=3.608\text{ in.}$), Moment, $Mx$ (kips $\text{ft/ft}$)
Example 1: Center Lift (em=5.5ft, ym=3.608in.), Shear Force, Qx (kips/ft)
Example 1: Edge Lift, (em=2.5ft, ym=0.752in.), Displacements (in.), (CT)
Example 1: Edge Lift (em=2.5ft, ym=0.752in.), Moment, Mx (kips ft/ft)
DESIGN ENVELOPES

Example

Soil Support Pattern

Worst Soil Support Patterns
Dry Season (-) Suction Ground Surface

Wet Season

Equilibrium

Dry Season

Depth
log(SUCTION)

Depth of the Moisture Active Zone

Wet Total Suction Limit for Clay

Equilibrium Suction for Non-Cemented Soils*

Matric Suction

Total Suction

Wiltting Point of Vegetation

From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russam and Coleman, 1961)
* From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russam and Coleman, 1961)
**log(SUCTION)**

- **Depth of the Moisture Active Zone**
- **Matric Suction**
- **Total Suction**
- **Wet Total Suction Limit for Clay**
- **Equilibrium Suction for Non-Cemented Soils**
- **Wilting Point of Vegetation**

* From Empirical Relation of Thornthwaite Moisture Index (Russam and Coleman, 1961)
log(SUCTION)

DEPTH, m

Matric Suction
Total Suction
Osmotic Suction
Wilting Point for Vegetation

*From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russan and Coleman, 1961)
Equilibrium Soil Suction vs. TMI

Equilibrium Suction - pF vs. Thornthwaite Moisture Index (Im)

\[ y = 3.6598e^{-0.0033x} \]

\[ R^2 = 0.356 \]

Standard Deviation = 0.25 pF
Crack Spacing Gets Larger with Depth
RUNOFF WATER

WATER SOAKS INTO SOIL

SUCTION RANGE BETWEEN CRACKS

SUCTION RANGE BETWEEN CRACKS

WATERSOAKS INTO SOIL

DRY LIMIT

WET LIMIT

2.0 pF

4.0 2.0

2.0
DEPTH BELOW SOIL SURFACE

CRACKING SPACING

SOURCE: MICHAEL KNIGHT
PH. D. DISSERTATION, GEOLOGY
UNIVERSITY OF MELBOURNE (AUSTRALIA)
1972
Field to laboratory diffusion coefficient ratio (Cont’d)

![Graph showing field to laboratory diffusion coefficient ratio with reliability on the y-axis and field $\alpha$/laboratory $\alpha_0$ on the x-axis, with different lines representing different depths $dc$.](image)
Drilled Pier Design

Retaining Wall Design
Lateral Earth Pressure Concept (1/5)

Suction Change
Lateral Earth Pressure Concept (2/5)

\[ \sigma_h = k_0 \gamma_i z = \left( \frac{3}{2} \right) \sigma_i 10 \frac{2 \varepsilon_h}{\gamma_i (1-\varepsilon)} \left( \frac{h_i}{h_f} \right) \frac{\gamma_h}{\gamma_i} - \frac{\gamma_i z}{2} \]

Suction Change

Lateral Pressure Due to Suction Change
Lateral Earth Pressure Concept (3/5)

Lateral Pressure Due to Suction Change

Limited by Soil Strength
Lateral Earth Pressure Concept (4/5)

(Small Suction Change)
At Rest Earth Pressure
Lateral Earth Pressure Concept (5/5)

Zone

I

II

III

Z_{mp}
Severe damage to a reinforced concrete columns due to differential heave, in Saudi Arabia (Al-Shamrani and Dhowian, 2003)
Retaining Walls

EXPANSION PRESSURE

RESISTING PRESSURE
3 – 4 ft
Horizontal Earth Pressure in Expansive Soils
Horizontal Swelling Pressure Model

\[ Z_{mp} = 3 - 5 \text{ ft} \]

- Joshi and Katti (1980); Komornik (1962); Brackely and Sanders (1992); Symons et al. (1989)

\[ Z_{mp} = 3 - 5 \text{ ft} \]

\[ z_{mp} \tan \left(45 + \phi'/2\right) = 5 - 7 \text{ ft} \]

\[ \sigma_h = \left(1 - \sin \phi'\right) \gamma_t z \]

Horizontal Active zone

\[ XZ_i = z_{mp} \tan \left(45 + \phi'/2\right) \left[1 - \left(\frac{z}{H}\right)^2\right] \]

- Richards and Kurzeme (1973) 4 times the overburden
- Joshi and Katti (1980) 42 psi @ 3 ft, lab
- Komornik (1962) 55 psi @ 3 ft, lab
- Brackely and Sanders (1992) 12 psi @ 3 ft, field
Fissures caused by a passive failure of the soil resulting from the horizontal pressure during seasonal swelling of the clay.

Mean angle of the fissure to the horizontal = 43 degree

Silckensides occurs in soil which has PI >30, -2μm>30

Leeuhof test site at Vereeniging, South Africa
Brackely and Sanders (1992)

Natural horizontal pressures measured in field

Seasonal range of suction (In situ psychrometers)

Maximum pressures measured at four depths in 1979, 1980, 1981 (In situ pressure cells)
Komornik (1962)
Measured horizontal pressures in the large scale pile test

Soil Properties
LL  76 %
PI  48 %
#200 90 %
-2μm 62 %

Site Kibbutz Mizra, Israel

Sand seam
**Kim and O’Neill (1998)**

**Axial behavior of the pier**

**Test Site Stratigraphy (NGES-UH)**

**Schedule of Rebar and Concrete in Drilled Shaft**
Kim and O’Neill (1998)
Axial behavior of the pier

Bar versus Time (1 bar = 100 kPa)

Uplift Force versus Time
Kim and O’Neill (1998)
Axial behavior of the pier

Suction (pF)

Swelling (in)

Horizontal Pressure (psi)

Pile Movement (in)

Axial Stress (psi)

Depth (ft)
Case Study of Bending Behavior of the Pier Uneven Wetting with Same Initial Condition

\[ Z_{mp} \cdot \tan \left( 45 + \frac{\phi'}{2} \right) \]

NGES-UH Site (Kim and O’Neill, 1998)
Case Study of Bending Behavior of the Pier
Uneven Wetting with Same Initial Condition

NGES-UH Site (Kim and O’Neill, 1998)
Case Study of Bending Behavior of the Pier
Uneven Wetting with Same Initial Condition

NGES-UH Site (Kim and O’Neill, 1998)
Retaining Wall Design
Katti et al. (1979)
Measured horizontal pressures in the large scale retaining wall test

Black cotton soil, India
LL  81.5 %
PI  38.3 %
#200 96.0 %
-2μm 56.0 %

3 months saturation
Katti et al. (1979)
Measured horizontal pressures in the large scale retaining wall test

Katti et al. (1979)
Measured horizontal pressures in the large scale retaining wall test
Case Study of Bending Behavior of the Retaining Wall

NGES-UH Site (Kim and O’Neill, 1998)
Case Study of Bending Behavior of the Retaining Wall

NGES-UH Site (Kim and O’Neill, 1998)
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• Shrinkage cracking design
• Shallow slope failure
• Slab-on-ground design
• Drilled pier design
  ➢ Lateral pressures
  ➢ Stresses, strains, movements
  ➢ Comparison with field measurement
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